

TanDEM-X: A Challenging Radar Mission for Generating a Next-Generation Earth's Topography

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Abstract— TanDEM-X (TerraSAR-X add-on for Digital Elevation Measurements) is a German Earth observation radar mission that consists of a synthetic aperture radar interferometer with two almost identical satellites flying in a closely controlled formation. With a typical separation between the satellites of 120 to 500 m interferometric data sets are acquired and processed to a global Digital Elevation Model (DEM) with 2 m relative height accuracy at 12 m posting. While the main mission phase for DEM data acquisition has been finished by mid-2014, the processing of the global (100% global land surface coverage including the poles) TanDEM-X DEM will be concluded in 2016. Final DEMs for more than 60% of all land masses are already available for scientific and commercial applications. The results achieved so far are well within the expected performance for the global DEM. A 15-month science phase of the TanDEM-X mission started in October 2014 which offers the opportunity to generate DEMs with even higher accuracy for selected areas, and to explore and demonstrate the new scientific applications of this unique mission. This paper provides an overview of the TanDEM-X and summarizes the current status and the quality of the available DEMs.

Index Terms—Synthetic Aperture Radar (SAR), Spaceborne SAR, Interferometry, Digital Elevation Model (DEM).

I. INTRODUCTION

TanDEM-X is the first radar interferometer in space that employs two satellites operating in a closely controlled formation flight. TerraSAR-X (TSX), the first satellite of the formation, was launched in June 2007 and is providing high-resolution X-band radar images for scientific [1], [2], [2] and commercial [4] applications. TanDEM-X (TDX), an almost identical satellite to TerraSAR-X, was launched in June 2010 [5] and is equipped with an additional 36 kg cold gas tank to allow precise maneuvers for keeping the formation flight. In addition, TanDEM-X has a larger solid-state mass memory with 768 Gbit (twice the size of TerraSAR-X) to support the on-board data buffering and downlink of the large data amount during interferometric acquisitions. While both radar satellites are operated during the interferometric acquisition mode, either the TerraSAR-X or the TanDEM-X satellite is used for acquiring high-resolution 2-D radar images.

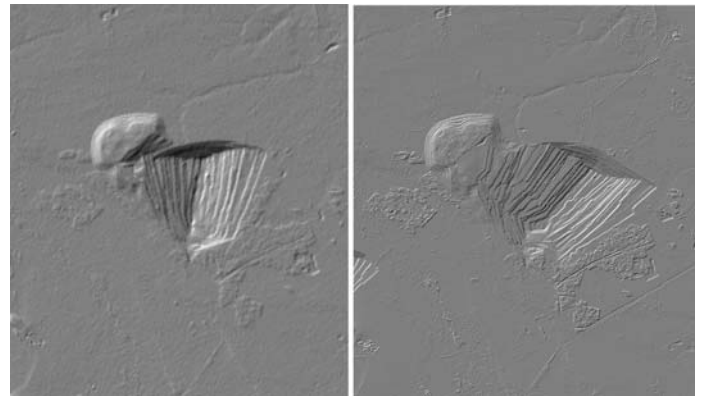


Fig. 1 – Comparison of SRTM 1 arcsec DEM (left, acquired in 2000) and TanDEM-X DEM (right, 2011) of a coal mining area in north-western Germany clearly showing the improved quality and the changes due to ten years of mining activity.

The primary objective of the TanDEM-X mission is the generation of a global Digital Elevation Model (DEM) of the Earth's surface with unprecedented accuracy as the basis for a wide range of commercial applications as well as for scientific research. It is expected that this data set will become a new reference in geosciences and remote sensing applications since its 3-D information content is ca. 30 times more accurate than the presently available global scale DEM data set. The first DEM data sets are available since January 2014 and the global DEM will be available by mid-2016.

TanDEM-X has an ambitious time schedule to reach its main mission goal. After the commissioning phase, the first four years were dedicated to the global DEM acquisitions. To facilitate dual-baseline phase unwrapping all land masses were covered at least twice in the same looking direction but with different baselines. Difficult mountainous terrain required additional acquisitions viewing from the opposite direction to allow filling gaps due to shadow and layover. The main mission phase dedicated to DEM acquisition has been finished by mid-2014. By the end of 2014 final DEMs for approx. 35% of the landmasses will be available. The data quality assessment shows that all specifications for the DEM accuracy are being met.

The baseline geometry in these first 4 years was optimized for DEM performance. A limited number of scientific

acquisitions was included during this first mission phase depending on the available satellite resources and the suitability of the baseline values for fulfilling the scientific requirements. With the start of the science phase in October 2015 the data acquisition and the baseline settings are now dedicated to the secondary objectives of TanDEM-X. Beyond the generation of a global DEM, local DEMs of even higher accuracy level (posting of 6 m and relative vertical accuracy of 0.8 m) and applications based on Along-Track Interferometry (ATI) like measurements of ocean currents are important secondary mission objectives. Along-track interferometry also allows for innovative applications to be explored and can be performed by the so-called dual-receive antenna mode on each of the two satellites and/or by adjusting the along-track distance between TSX and TDX to the desired value. Furthermore, TanDEM-X supports the demonstration and application of new SAR techniques, with focus on multistatic SAR, polarimetric SAR interferometry, digital beam forming and super resolution.

II. THE GROUND SEGMENT

The missions TerraSAR-X and TanDEM-X jointly share the same space segment consisting of the TSX and TDX satellites orbiting in close formation and are operated using a common ground segment, that was originally developed for TerraSAR-X and that has been extended for the TanDEM-X mission [6]-[9]. Specific new developments are described in the following paragraphs.

The spatial baseline between the TSX and TDX is derived at millimeter accuracies from on-board GPS measurements taken by the two-frequency Integrated GPS Occultation Receivers (IGOR).

A key issue in operating both missions jointly is the different acquisition scenarios: whereas TerraSAR-X requests are typically single scenes for individual scientific and commercial customers, the global DEM requires a global

mapping strategy. This strategy has also to account for the current formation flying geometry which, in turn, depends on the orbit parameters selected and for any given orbit configuration permits generating a digital elevation model only within a certain latitude range.

The two satellites downlink their data to a global network of ground stations: Kiruna in Sweden, Inuvik in Canada, and O'Higgins in the Antarctic. The global data acquired in the last 4 years for the digital elevation model alone absorb a total data volume of more than 350 Terabytes. After a brief quality check, the data have been recorded on tape and shipped to DLR in Oberpfaffenhofen for processing and archiving.

The entire processing chain is a new TanDEM-X specific development. Major design drivers result from the acquisition strategy which requires the combination of several (global) coverages and application of multi-baseline processing techniques based on supporting intermediate products. Absolute height calibration relies on a selected set (in average about 100 points per 1 by 1° DEM tile) of reference points of the globally distributed elevation data provided by the laser altimeter from NASA's ICESat mission.

III. CLOSE FORMATION FLIGHT

An orbit configuration based on a helix geometry has been selected for safe formation flying. The helix like relative movement of the satellites along the orbit is achieved by combination of an out-of-plane (horizontal) orbital displacement imposed by different ascending nodes with a radial (vertical) separation imposed by the combination of different eccentricities and arguments of perigee. Since the satellite orbits never cross, the satellites can be arbitrarily shifted along their orbits. This enables a safe spacecraft operation without the necessity for autonomous control. Cross- and along-track baselines ranging from 120 m to 10 km and from 0 to several 100 km, respectively, can be accurately adjusted depending on the measurement requirement [8].

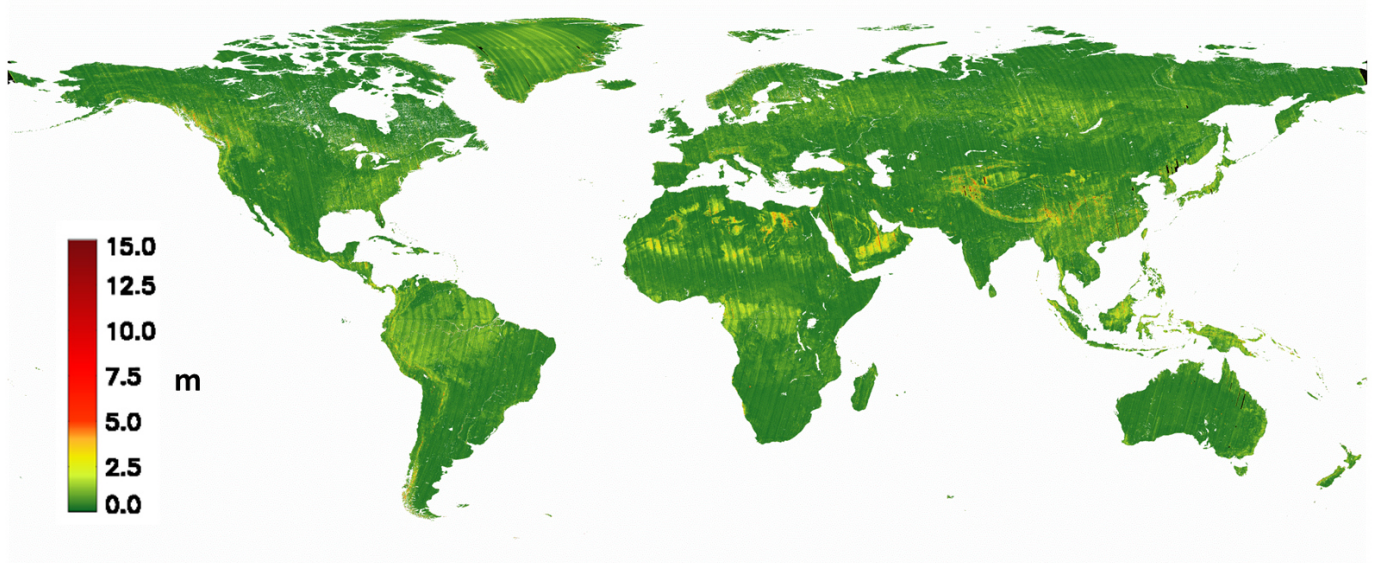


Fig. 2 - Predicted relative height accuracy of the TanDEM-X DEM derived from the interferometric coherence after the first and second global acquisition which were performed from December 2010 until March 2013. Subsequent data acquisitions until mid-2014 are not included in this prediction.

IV. MISSION STATUS AND OUTLOOK

After the launch in June 2010, the TDX SAR system was calibrated and its performance was verified to be as good as for TSX. Following comprehensive testing of the various safety measures close formation was achieved mid October 2010 and the operations at typical distances between 120 and 500 m is running remarkably smooth and stable since then.

The subsequent bistatic commissioning phase of the TanDEM-X mission concentrated on checking out the complete bistatic chains from acquisition planning to bistatic and interferometric processing and generation of so-called Raw DEMs. Global DEM acquisitions started in December 2010. Parallel to the first month of operational data acquisition the team concentrated its efforts on the calibration of the bistatic interferometer. Correction of differential delays between TSX and TDX was necessary to facilitate the utilization of radargrammetry for resolving the 2π -ambiguity band. A comprehensive monitoring system has been established to evaluate the performance of each individual data take and provide feedback to the TanDEM-X acquisition planning for additional acquisitions. Phase, delay and baseline calibration have reached such an accuracy level [11], that more than 90% of all Raw DEMs are within ± 10 m of DEM derived from SRTM/ICESat data already before the final calibration step using ICESat data (approximately 100 points per 1 by 1o DEM tile) as reference heights.

The first and second global coverage (except Antarctica) were completed in January 2012 and March 2013 respectively. After some gap-filling, Antarctica was mapped for the first time under local winter conditions. In early August 2013 the helix formation was changed to allow imaging of mountainous areas from the opposite viewing geometry. To enable the highly successful dual-baseline phase unwrapping also for these areas a third and fourth coverage was acquired. Afterwards the satellite were maneuvered back to the original formation and Antarctica was covered again at larger

baselines. The primary data acquisition program was concluded by mid-2014. Since then gap-filling is being performed in parallel to the science phase.

Until the end of the science phase in December 2015 even more accurate DEMs on local scales will be generated. Applications based on Along-Track Interferometry (ATI) and new SAR techniques, with focus on multistatic SAR, polarimetric SAR interferometry and digital beam forming will be demonstrated.

V. CONCLUSIONS

Accurate calibration of radar system delay, phase synchronization between the TSX and TDX radar systems as well of the interferometric baselines have been successfully carried out showing excellent system performance. While the main DEM acquisition phase has been finished in mid-2014, the generation of the global TanDEM-X DEM has commenced and about 35% of the land surface is already available. The results achieved so far are well within the expected performance for a global DEM with 2 m height accuracy.

During the science phase of TanDEM-X, DEMs of even higher accuracy will be produced for selected areas. In addition, this dedicated mission phase featuring interferometric acquisitions with flexible and even larger baselines in experimental modes is focused in the demonstration of the scientific capabilities of this unique mission.

TanDEM-X has demonstrated the feasibility of an interferometric radar mission with close formation flight and delivers an important contribution for the concept and design of future SAR missions. One example is Tandem-L, a mission proposal for monitoring dynamic processes on the Earth surface with unprecedented accuracy [12], [13].



Fig. 3 - Perspective view using a Digital Elevation Model (DEM) generated by TanDEM-X over the Finke Gorge National Park, close to Alice springs, Australia.

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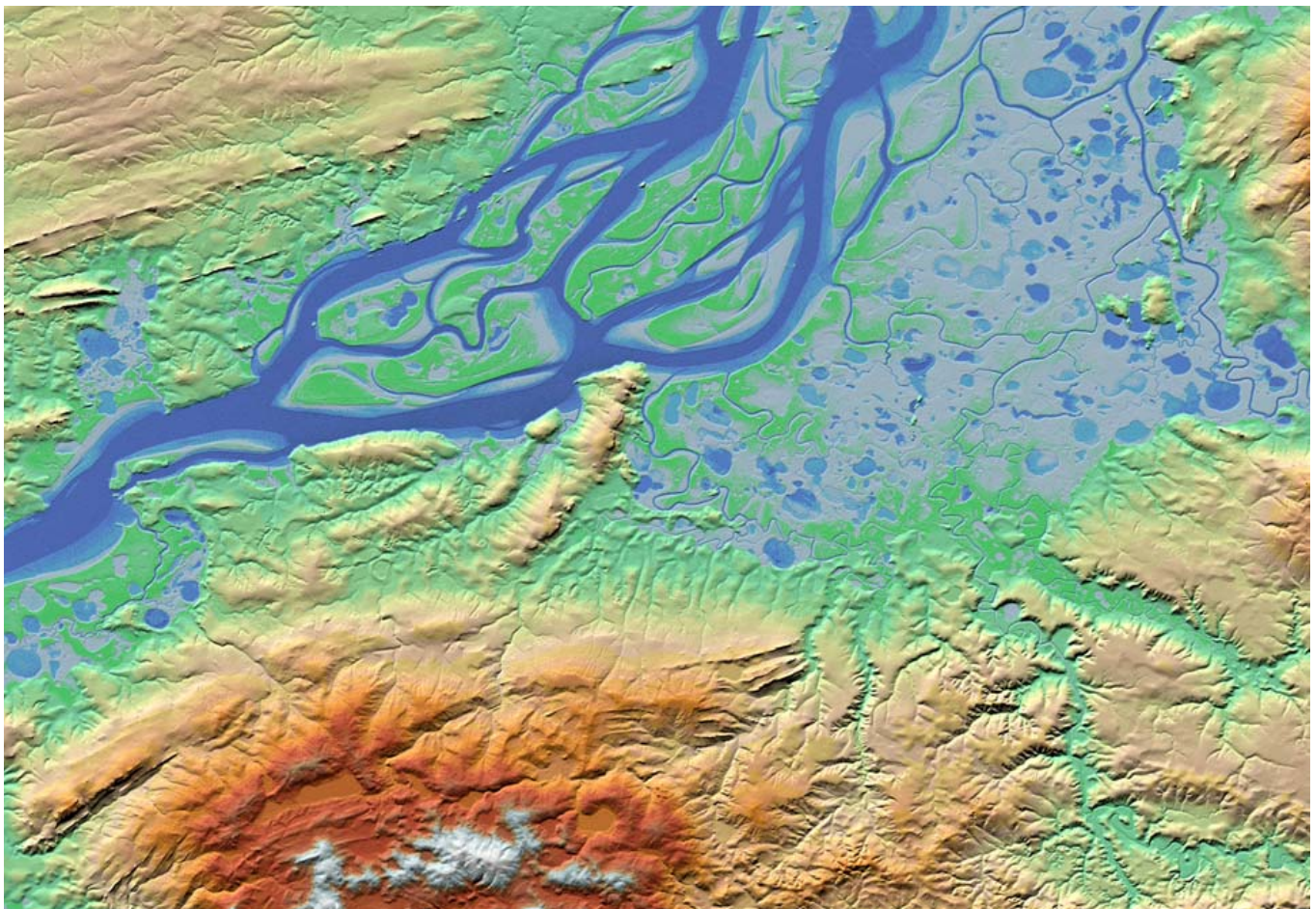


Fig. 4 - Digital Elevation Model (DEM) generated by TanDEM-X over Kara Sea, Pyasina river, Russia